Evolution of magnetotelluric, total magnetic field, and VLF field parameters in Central Italy: relations to local seismic activity

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Abstract
Magnetotelluric data were collected at Collemeluccio (41.72°N, 14.37°E) in Central Italy from summer 1991 to spring 1998. Analyzed by means of tensor decomposition on the geoelectric potential and robust estimation on the geomagnetic field, this set of data allowed the investigation of the electric properties at different time-periods. The variation of some indicators, related to the phenomenon of electromagnetic induction, is presented here in its time evolution and compared to local and regional seismic activity. Tectonomagnetic field observations from absolute magnetic field level in Central Italy were also made on data simultaneously recorded at four magnetometer stations, using L'Aquila Geomagnetic Observatory as a reference for differentiation. Recent results gathered from a system of two VLF search coil wide-band antennas, installed in the L'Aquila Observatory, are also discussed in relation to local seismic activity.

Key words *magnetotelluric – tectonomagnetism – VLF waves*

1. Introduction

The area extending in Central Italy between latitudes 41.7° and 42.4°N and longitudes 12.9° and 14.4°E has been instrumented with a magnetotelluric station, magnetometer total field stations and VLF natural wave detection systems (fig. 1). The deployment of these instruments was made in the framework of a program of electromagnetic and magnetic natural signals detection in a seismically active area as well as to have a better knowledge of the natural electromagnetic phenomena observed in this region, where the Geomagnetic Observatory of the Istituto Nazionale di Geofisica, L'Aquila, is also located. The area is very interesting in the tectonic and geodynamic frame of the Italian peninsula, with a long history of seismic events that make it suitable for the search of possible relations between electromagnetic natural phenomena and seismic activity.

Earthquakes distribution in Italy roughly follows the NW-SE trend of the Apennine mountain belt. Focal mechanisms indicate that this chain is presently dominated by extensional deformation accomplished by NW-SE normal faulting (*e.g.*, Anderson and Jackson, 1987) overimposed on the Paleogene compressional structures. In the Central Apennines, where the study area is located, the M = 6.9 Avezzano

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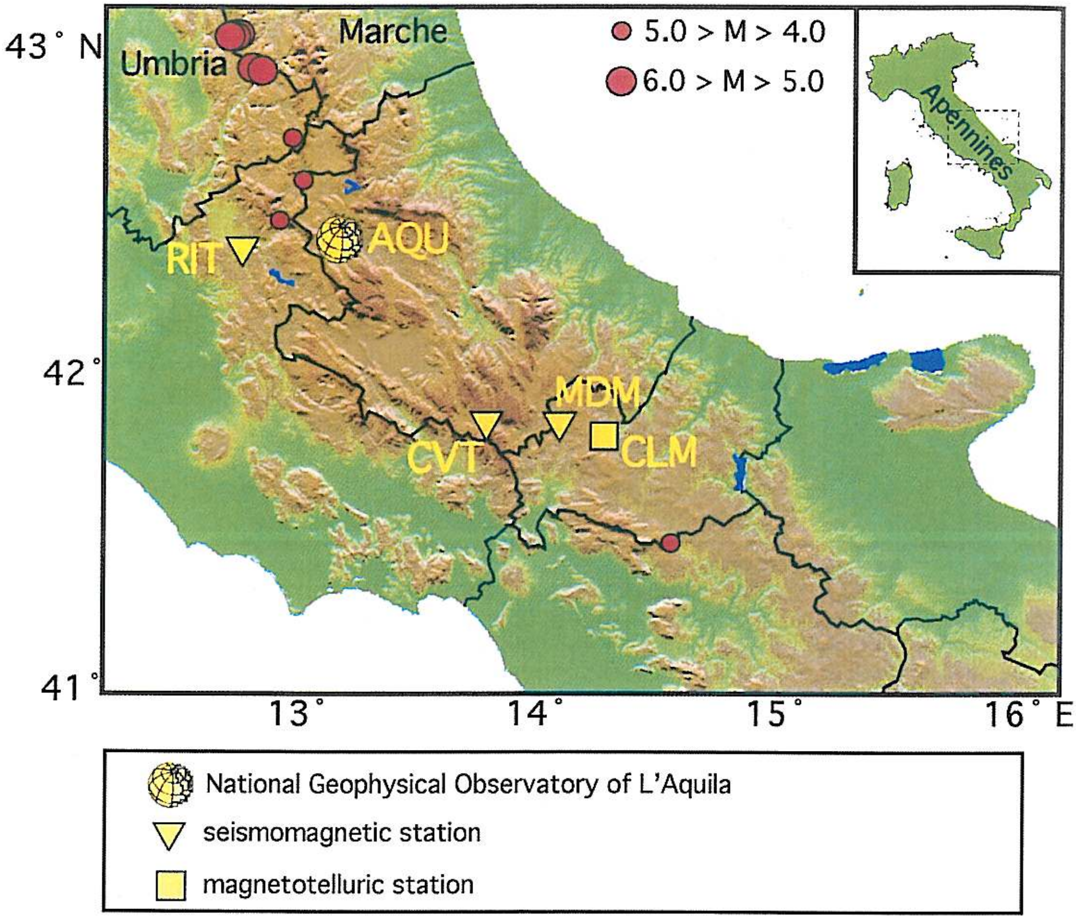

Fig. 1. Map of Central Italy showing Proton Precession Magnetometers (PPM) and magnetotelluric stations used in this work (see table I) and the epicenters (red dots) of magnitude $M \geq 4.0$ earthquakes which occurred in the study period (table II). Topography and administrative regional boundaries are also shown.

earthquake took place in 1915 (*e.g.*, Ward and Valensise, 1989). Other important events can be recalled for this area in recent years: the $M = 5.4$ Val Comino earthquake in 1984 (Console *et al.*, 1989) and the long seismic sequence, with six earthquakes of magnitude between 5.0 and 6.0 occurring in September-October 1997 in the Umbria Marche regions (Amato *et al.*, 1998), north of the area to which this paper refers (fig. 1). Apart from the Umbria-Marche seismic sequence, which is marginal to the study area, the local seismicity is characterized by crustal

Table I. Acronyms, name and locations of the L'Aquila Geomagnetic Observatory (AQU), seismomagnetc (CVT, MDM, RIT) and magnetotelluric (CLM) stations used in this work.

Code	Station	Latitude N	Longitude E
AQU	L'Aquila	42.366	13.316
RIT	Rieti	42.333	12.916
CVT	Civitella Alfedena	41.766	13.866
MDM	Monte di Mezzo	41.750	14.200
CLM	Collemeluccio	41.716	14.366

Table II. Parameters of earthquakes with magnitude $M > 4.0$ occurred in Central Italy during the study period. Δ indicates the epicentral distance from seismomagnetic and magnetotelluric stations located within 100 km.

#	Origin time		Epicenter		M	Epicentral distance				
	day/month/year	h:min	Lat. (N)	Long. (E)		Δ_{AQU}	Δ_{RIT}	Δ_{MDM}	Δ_{CVT}	Δ_{CLM}
1	20/10/96	19:06	42.559	13.163	4.0	23.7 km	31.5 km	–	–	–
2	19/03/97	23:10	41.383	14.630	4.1	–	–	54.9 km	76.1 km	43.0 km
3	26/09/97	00:33	43.018	12.913	5.6	75.3 km	78.4 km	–	–	–
4	26/09/97	09:40	43.024	12.926	5.8	76.0 km	78.6 km	–	–	–
5	03/10/97	08:55	43.023	12.890	5.0	75.9 km	79.8 km	–	–	–
6	06/10/97	23:24	43.010	12.918	5.4	74.5 km	77.5 km	–	–	–
7	12/10/97	11:08	42.897	13.008	5.1	62.3 km	62.9 km	–	–	–
8	14/10/97	15:23	42.907	12.969	5.5	63.1 km	65.3 km	–	–	–
9	15/08/98	05:18	42.444	13.059	4.6	16.3 km	22.6 km	–	–	–
10	10/10/99	15:35	42.691	13.127	4.0	38.0 km	42.6 km	–	–	–

events of maximum magnitude 4.6 (table II). Lithotypes outcropping in the Central Apennines are mainly carbonates and marls with continental and flysch deposits (marls, clays and sandstones). Rock magnetization is locally moderate to low (Molina *et al.*, 1994).

Several research groups have tried to relate observations of magnetotelluric, magnetic and electromagnetic variations to seismic events, or more generally to tectonic events. Such studies have been undertaken in many active seismic regions of the world. Interesting examples come from experiments made in U.S.A., Japan, Russia (and more generally former Soviet Union) Europe and others. The scientific literature abounds in such examples; *e.g.*, refer to reviews by Parrot and Johnston (1993), Hayakawa and Fujinawa (1994), Johnston (1997), and also to journal issues by Johnston and Parrot (1997), Gasparini *et al.* (1997), devoted to such topics. In this framework, we should also mention the long ongoing debate, on the so called VAN method that aims at the prediction of earthquakes in Greece by detecting anomalous electric signals (*e.g.*, *Geophysical Research Letters* issue of May 27th , 1996).

Many of the papers dealing with electromagnetic methods related to seismology are devoted to the observation and explanation of peculiar phenomena observed in seismic areas, generally characterized by anomalies in time variation of some electromagnetic parameters. In fact, apart from induction from natural magnetic time variations, contributions from natural internal sources (like tectonic activity) are also possible. In some cases, these observations have been claimed to be precursors of earthquakes. However, patterns of time variations of electromagnetic or magnetic parameters vary generally greatly in shape, time scales and extent around the seismic focus and also the definition of 'anomaly' is sometimes very difficult to express quantitatively. In this paper we discuss the time evolution of some classical magnetotelluric parameters (*e.g.*, apparent resistivity and phase shift) recorded by one magnetotelluric station installed in the study area and its possible relation to earthquake occurrence. For previous investigations in the same area refer to: Ernst *et al.* (1994, 1997); Meloni *et al.* (1996).

In the present study, the investigation of crustal generation of local magnetic fields accompanying seismic activity, which is the aim of tectonomagnetic studies (see for example, Mueller and Johnston, 1998), was undertaken by means of a seismomagnetic network made of Proton Precession Magnetometers (PPM) installed in

Central Italy (fig. 1). Piezomagnetic fields can be produced by dislocation sources, see for example Sasai (1994). For previous investigations in the same area refer to (Mele *et al.*, 1994, Meloni *et al.*, 1998). Finally, recent results from a VLF wave detection system installed in L'Aquila Observatory are described. VLF emissions can also in fact be related to electric and magnetic fields generated by stress induced (piezoelectric) phenomena in the seismogenic areas (*e.g.*, Morgounov *et al.*, 1994).

2. The experimental apparatuses

The experimental design of the instrumentation used in the mentioned investigations in electric, magnetic and electromagnetic studies in seismic and tectonically active areas and also in volcanic areas, can be found in the aforementioned literature. In order to give information on the technical aspects of the data used in this work, a short description of the instrumentation used is reported in the following.

2.1. *The magnetotelluric station at Collemeluccio*

A data acquisition system for long term magnetotelluric investigations was installed in 1991 at Collemeluccio (Meloni *et al.*, 1996). The station is composed of a torsion magnetometer with a photoelectric transducer for the measurement of the magnetic field time variation in three orthogonal components. Whilst for the measurements of spontaneous electric potential phenomena, polar electrodes, consisting of porous porcelain elements, containing a cupric sulphate, were connected to two electric lines around 100 m apart respectively in N-S and E-W directions. The instrumentation is completed by a low noise and linear filter preamplifier. Data are gathered using a 14 bit A/D converter and a cassette tape recorder. The systematic sampling took place every 20 s (Jankowsky *et al.*, 1984). Interesting changes in the magnetotelluric parameters were found in previous analyses and compared to some seismic events (Ernst *et al.*, 1997).

2.2. *The seismomagnetic network*

The investigation of possible tectonomagnetic fields in Central Italy started with the installation of a seismomagnetic network in mid 1989. Data are gathered by means of PPMs installed in a network with station separation of a few tens of kilometers. Magnetometers simultaneously measure the total magnetic field intensity with a sampling rate that has been variable in the last ten years (4-10-15 min). High accuracy is required in the measurements since the expected amount of change in the total field intensity for a tectonomagnetic or seismomagnetic effect is of the order of 1 to 5 nT, as demonstrated by experimental observations and theoretical models. Instrument accuracy is 0.1 nT and the expected drift is 0.2 nT/yr. In order to detect possible time-dependent magnetic field anomalies, data are differentiated at each station with respect to the reference site of L'Aquila. The analysis of data from 1989 to 1995 (Meloni *et al.*, 1998) revealed a variation of 5 nT in the geomagnetic field over a two-month period (January-February 1990).

2.3. *The L'Aquila Observatory*

The magnetic observatory – The main Italian geomagnetic observatory of L'Aquila is located about ten kilometers north-west of the city of L'Aquila. Here continuous recording of geomagnetic elements H and Z (horizontal and vertical intensities), D declination and F total field, have been made since the International Geophysical Year (1957/1958). As now a digital recording system made out of an automatically recording proton vector magnetometer and a second automatic set made of a three element flux-gate and an Overhauser effect magnetometer, are working.

The telluric lines – The telluric station at L'Aquila is made of two orthogonal NS and EW 140 m lines and two polar electrodes consisting of porous porcelain elements containing a cupric sulphate gel. A fifth neutral point is used. The station is furnished with a two independent channel amplifier with 200 gain and two anti-aliasing fourth order filters set at 1 Hz. Sampling is made at 5 s (16 bit resolution).

The VLF noise antenna system – The station at L'Aquila also monitors time variability of natural signals in VLF band by means of two search coil wide band antennas in the range 15-40 kHz; the instrument uses a low noise preamplifier and 4 band pass filters centered at 15, 20, 30 and 40 kHz. Radiometer sensitivity is 200 fT at 40 kHz. Sampling is made at 1 Hz and averaged at 20 s (12 bit resolution).

3. Data analysis

3.1. *Magnetotellurics at Collemeluccio*

The analysis of magnetotelluric measurements recorded at Collemeluccio over a large time window represents a valuable tool to detect some distinctive markers in different time-windowed observations. The grouped plots in the panels of figs. 2 and 3 show the evolution of the tensor impedance determinant, the corresponding phase and the skewness for the entire year 1997 and for the month of September 1997 respectively in detail. As known, such magnetotelluric quantities are invariant to coordinate system rotation. Adopting their usual definitions, we have

$$\mathrm{Det}\ Z = [(Z_{xx}(\omega)Z_{yy}(\omega) - Z_{xy}(\omega)Z_{yx}(\omega)];$$

$$\mathrm{phase} = \arg\ (\mathrm{Det}\ Z)$$

and

$$\mathrm{skew} = [Z_{xx}(\omega) + Z_{yy}(\omega)]/[Z_{xy}(\omega) - Z_{yx}(\omega)]$$

where Z_{ij} is a complex component of the impedance tensor (a function of frequency). Such invariant parameters, calculated by means of Egbert's code on time sequence of data segments, are averaged on the period intervals 10^2-10^3 s and 10^3-10^4 s (Egbert, 1997, available in Internet). The points in each time interval represent the mean value for the related decade.

On a global scale, the basic considerations refer to the assumption that such parameters vary in time and show significant changes both on long and short periods. They could be monitored to discover possible correlations with other geophysical quantities, and in case, under appropriate conditions, be related to the preparatory phases that take place prior to an earthquake. Moreover, the differences in the shapes between the two time-interval decades, give evidence that different physical processes may occur at different depths as inferred by different time-windows. This last evidence is supported by the different behavior of the skew parameter in the two decades: values greater than 0.5, mainly characterizing the 10^3-10^4 s decade, indicate 3D underground structures (Vozoff, 1972) while at shallow depth, the same site shows a 1D or 2D nature.

For the year 1997, during which, on September 26, a strong earthquake was located in the regions of Umbria and Marche, about 100 km away from Collemeluccio, the tensor invariant evolution, the phase angle variation as well as skewness, respectively in two bands 10^2-10^3 s and 10^3-10^4 s, are shown in fig. 2. Looking at this time evolution a remarkable annotation concerns the isolated strongly increased value during the month of August and September for 10^3-10^4 s decade. No particular changes can be found on the other parameters. In addition, no particular changes can be found in the daily averaged values for the month of September 1997 (fig. 3) where the very high values of the tensor invariant, with respect to the values in the months before August and after September, is however confirmed.

3.2. *Seismomagnetic network*

Measurements of the total magnetic field intensity *F* simultaneously recorded by three seismomagnetic stations (CVT, MDM, RIT) and by L'Aquila Geomagnetic Observatory (AQU) are averaged on a daily basis for the years 1989 to 1999 (fig. 4). Gaps in the data set are primarily due to technical problems and to weather conditions. From the daily means of the geomagnetic field intensity recorded at L'Aquila Observatory, the averaged values recorded at the other stations are subtracted for the time interval 1995-1999 (fig. 5a). This is also done for five-day

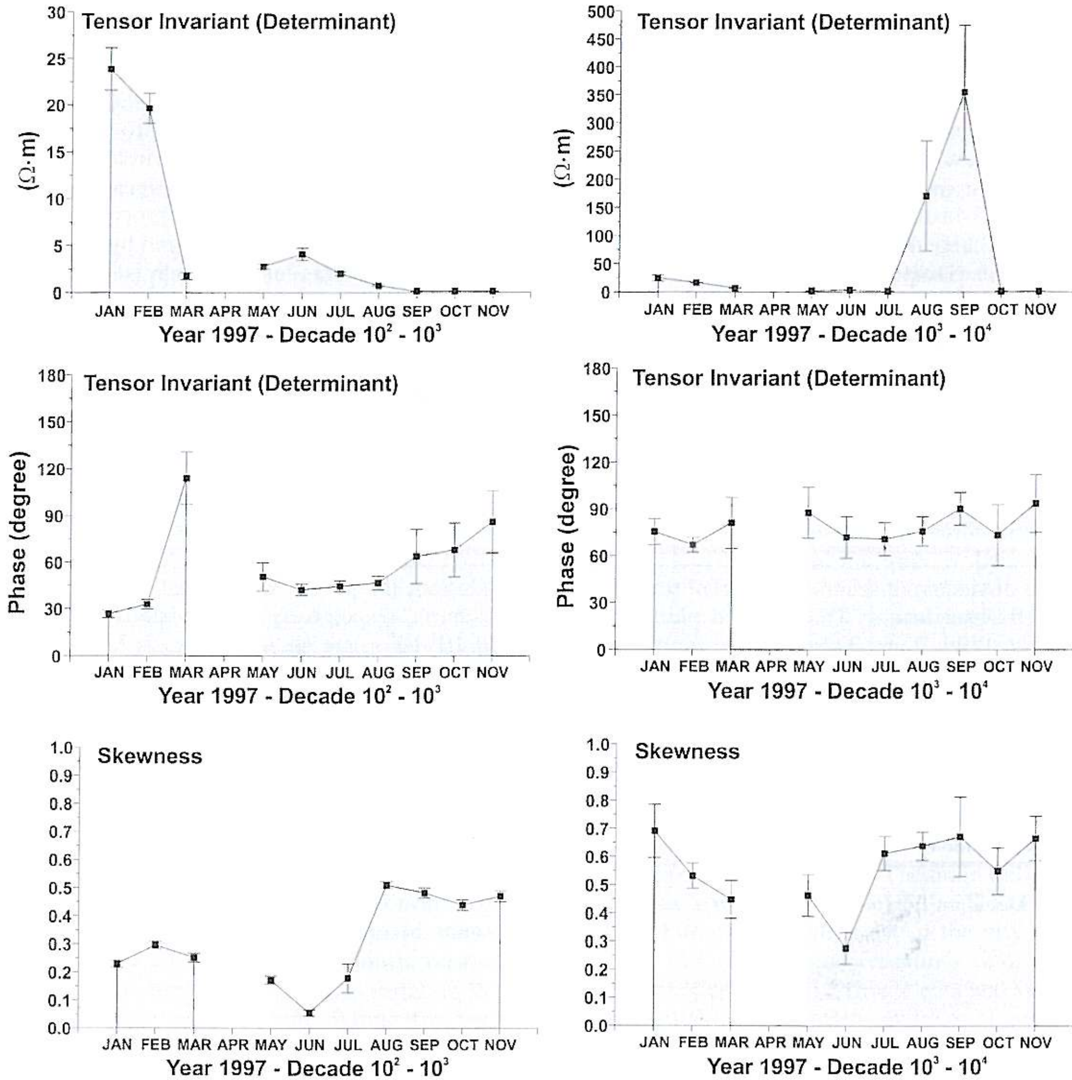

Fig. 2. Modulus, phase of the invariant tensor determinant for the two time-decades 10^2-10^3 and 10^3-10^4 s and skewness parameter: for the year 1997 at Collemeluccio, the mid term evolution is shown by the monthly mean values in each month. Missing points correspond to missing data segments.

averages (fig. 5b). The data analysis for the years 1989-1995 is reported in Meloni *et al.* (1998). The differentiation process between station pairs is necessary to filter out the contribution of sources not related to possible tectonomagnetic fields, such as magnetic field effects due to Earth external electric currents, and related fields induced in the Earth's interior. Differentiation also eliminates the effect of variations of the Earth's core electric currents

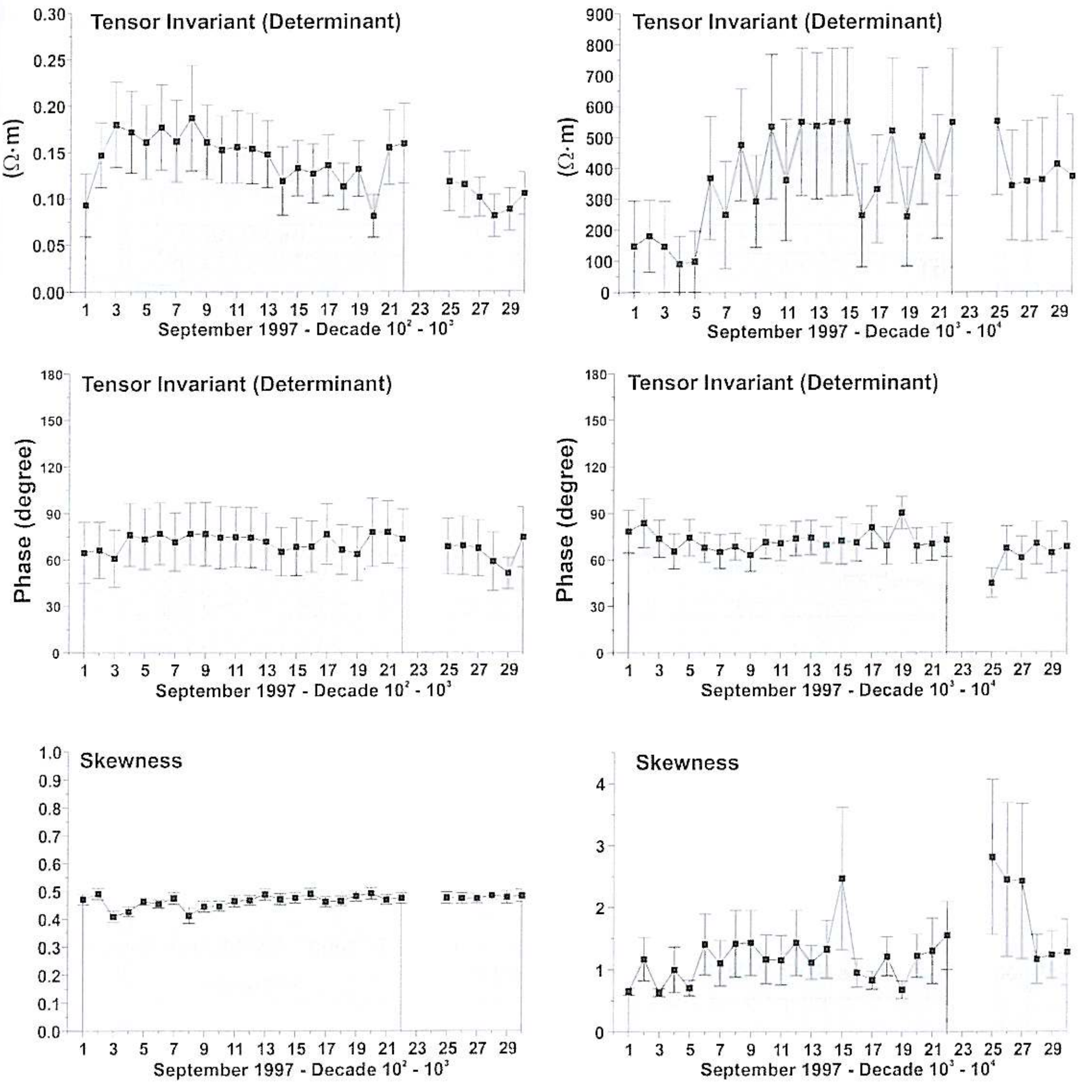

Fig. 3. Modulus, phase of the invariant tensor determinant for the two time-decades 10^2-10^3 and 10^3-10^4 s and skewness parameter: for the month of September 1997 at Collemeluccio, daily variation of tensor invariant elements is shown. Missing points correspond to missing data segments.

(*i.e.* large part of the non-uniform secular variation). The remnant non-zero differences reflect local changes in crustal magnetization due to variations of the stress field (tectonomagnetic effect).

3.3. *VLF station*

The time variability of natural signals, measured at L'Aquila Observatory in the VLF band by means of two search coil wide band anten-

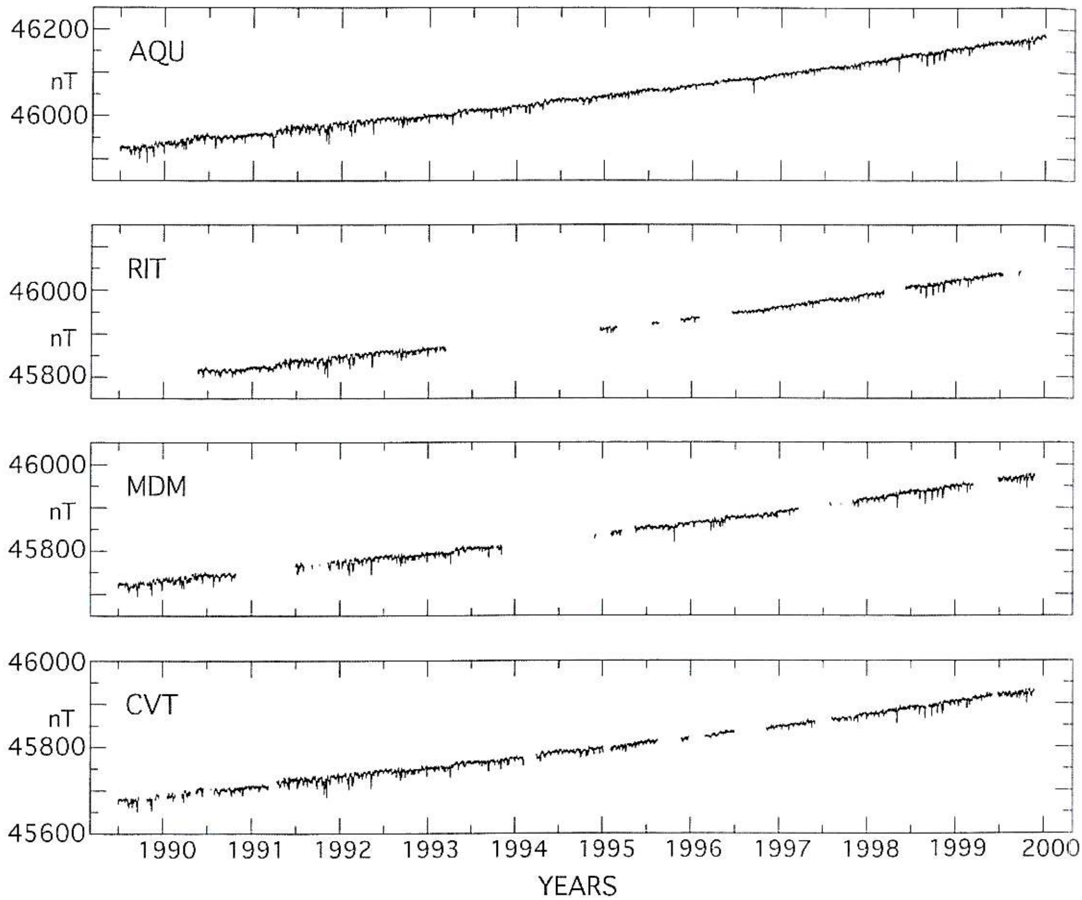

Fig. 4. Time variation of total magnetic field F (daily means) at L'Aquila Observatory (AQU) and the seismomagnetic stations (CVT, MDM, RIT) from July 1989 to 1999.

nas in the range 15-40 kHz, is discussed in Meloni *et al.* (1992). In the present paper, this variability is shown for the months of September and October 1997 in fig. 6 as the VLF 15-25 kHz integrated daily averages; black dots show earthquakes occurrences and dots size shows their respective magnitudes. In fig. 7 VLF 15-40 kHz integrated averages, represented by the hourly averages for the months of September and October 1997, are also shown and, as in fig. 6, black dots show earthquakes occurrences and dots size shows their respective magnitudes.

4. Discussion and conclusions

Results of the analysis of three different data sets collected in Central Italy, in the framework of a program of electromagnetic and magnetic natural signals detection in a seismically active area, are presented in this paper. The study area has a long history of seismic events. Anomalies in time variation of the electromagnetic and magnetic observed parameters are sometimes sought to establish possible connections with seismic activity. As above mentioned, however, time variations of electromagnetic or magnetic

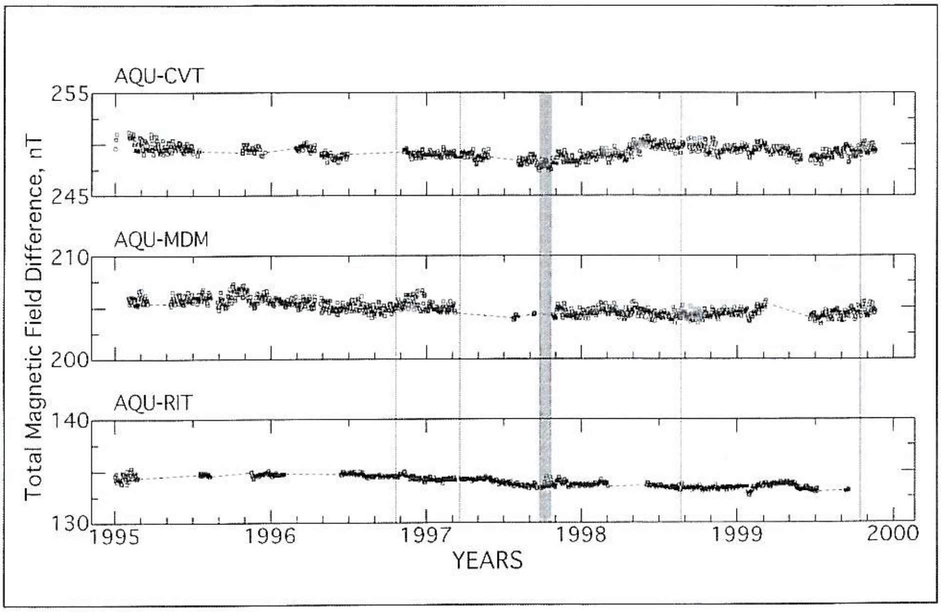

Fig. 5a. Daily-mean differences between L'Aquila Geomagnetic Observatory (AQU) and the seismomagnetic stations CVT, MDM, RIT from 1995 to 1999. Vertical bars indicate earthquakes with $M \geq 4$ (table II).

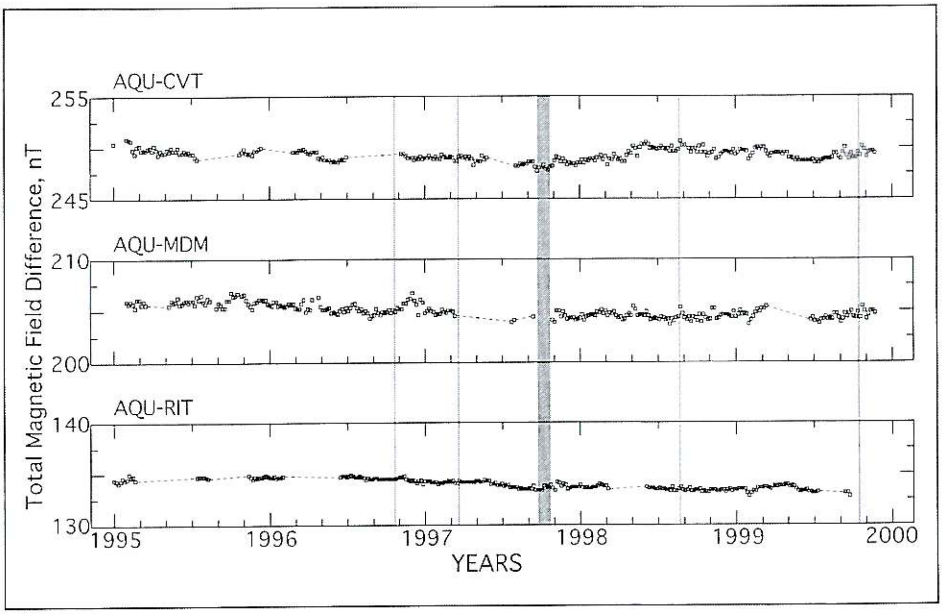

Fig. 5b. Five-day mean differences between L'Aquila Geomagnetic Observatory (AQU) and the seismomagnetic stations CVT, MDM, RIT from 1995 to 1999. Vertical bars indicate earthquakes with $M \geq 4$ (table II).

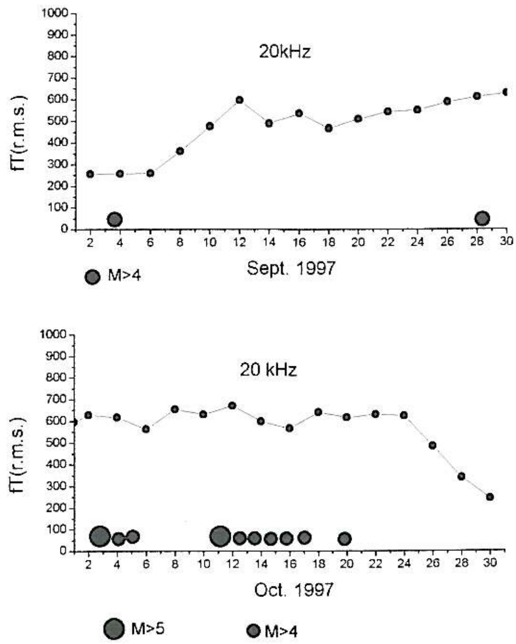

Fig. 6. VLF 15-25 kHz integrated daily averages for the months of September and October, 1997. Black dots show earthquakes (sized with magnitude).

parameters might vary greatly in shape, time scales and extent around the seismic source. Furthermore the definition of 'anomaly' is also sometimes very difficult to express quantitatively. For these reasons, when we gathered our data in recent years, we tried to evaluate our results not only in the search of possible correlation to seismic activity, but also in the framework of a contribution to a better knowledge of the electromagnetic environment in a seismically active area.

In recent years, a moderate seismic activity was recorded in the area. The most intense seismic activity (six shocks with magnitudes between 5.0 and 6.0, that hit the Umbria-Marche area, slightly north of L'Aquila) during September-October 1997 took place in an area that is only marginal to the monitored area.

As regards the CLM magnetotelluric station, it was found that right before and during the series of earthquakes with magnitudes over 5 which occurred at the end of 1997, significant changes were found in the magnetotelluric tensor invariant. Long-term changes in the impedance tensor invariants (determinant and skewness), when found from magnetotelluric data,

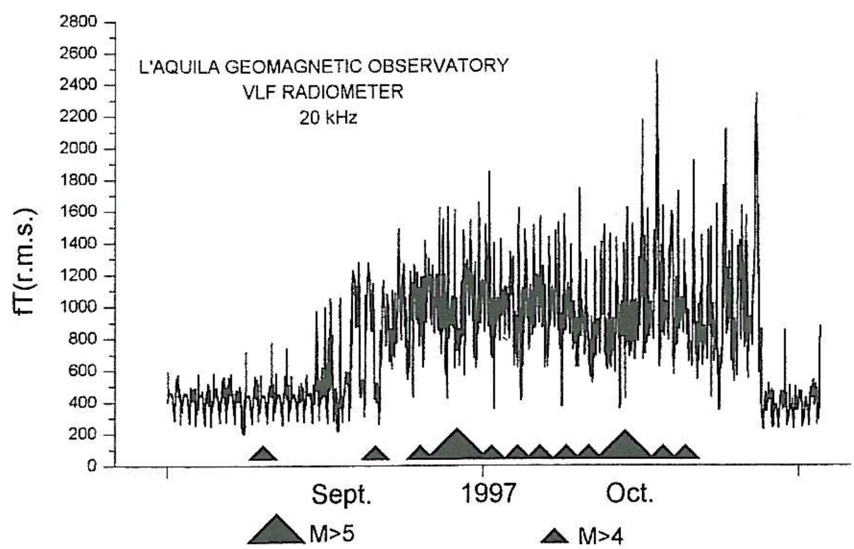

Fig. 7. VLF 15-40 kHz integrated averages shown by the hourly averages for the months of September and October 1997. Black triangles show earthquakes (sized with magnitude).

might also be explained as premonitory processes in the preparation of earthquakes, in particular due to water infiltration or migration along cracks. Such processes may significantly change electrical resistivity and strength parameters in the earthquake source zone. If one of these processes takes place in a large zone around the earthquake focus, the observed variations could reasonably be related to the observed seismic events.

The overall picture of total magnetic field differences in the 1995-1999 time window, as measured comparing the three seismomagnetic stations CVT, MDM, RIT and L'Aquila is shown in figs. 5a and 5b, for daily means and for five-day averages, respectively. Vertical lines indicate time occurrence of the earthquakes listed in table II (magnitude ≥ 4). The seismic sequence of September-October 1997, where six earthquakes with magnitude ≥ 5 took place in the Umbria-Marche region, is reported as a thick gray vertical line. The plots show an almost constant pattern without evidence of peculiar time variations of crustal magnetic field. The scatter around the mean difference values increases with the distance from L'Aquila Observatory showing the limits in the removal of external magnetic field variation gradients. Although some moderate seismicity occurred in recent years and at times significant anomalies have been detected from this network, it was not easy to identify a clear one-to-one relation between tectonomagnetic anomalies and seismic events. This could indicate that magnetic or long-term electric field variations of crustal origin, *i.e.* tectonomagnetic effects of piezomagnetic or electrokinetic origin, do not occur frequently in this area (Mele *et al.*, 1994; Meloni *et al.*, 1998).

The L'Aquila Observatory VLF integrated averages time variations, reported by the hourly averages for the months of September and October 1997, clearly show strong enhancements in correspondence with the earthquake occurrences. This effect appears somehow very clearly. A qualitative explanation may be related to rock creeping that takes place in the earthquake focal area and the intensive strain rate in the surrounding crust, that can give a mechanical background for the generation of electromagnetic anomalous fields (*e.g.*, Morgounov *et al.*, 1994). Although a deeper analysis of these signals is necessary before conclusions can be reached, it seems that the continuous monitoring of VLF integrated averages time variations maybe a promising approach in the assessment of earthquake electromagnetic related phenomena in this area.

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